

**CONSIDERATIONS FOR THE DESIGN, IMPLEMENTATION, AND EFFECTIVE
OPERATION OF SANDIA'S SUPER-POWER GENERATORS**

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Summary

After firing its first full power, 36-module shot on June 28, 1980, on schedule and on budget, the PBFA-I Accelerator progressed from an output parameter characterization phase through a stable operating point optimization phase and into an operational phase for conducting advanced power flow studies and ion beam driven inertial confinement fusion experiments. This paper describes the development of the PBFA Facility from the viewpoints of facility and accelerator design criteria, implementation of these designs, and effective operation.

Introduction

The first-generation Particle Beam Fusion Accelerator (PBFA-I)¹, developed by Sandia National Laboratories' Particle Beam Fusion Program, is the latest in a series of pulsed power generators of increasing output power and energy (Hydra, 35 kJ, 0.4 TW, 1971; Proto I, 20 kJ, 1 TW, 1974; Proto II, 300 kJ, 10 TW, 1976; and PBFA-I, 1 MJ, 30 TW, 1980). PBFA is significantly different than earlier accelerators in the program in several respects. First, its large physical size required the construction of a specialized high-bay laboratory with large capacity insulating gas, oil, and deionized water support systems and well engineered electrical and mechanical support subsystems. Second, its multi-modular design incorporating 36 independently controllable outputs of either positive or negative polarity required more advanced control of charging, firing, module synchronization, and electrical diagnostics capability than the manual control and data acquisition systems of earlier accelerators. Third, the more advanced PBFA pulse forming and power conditioning components, many of which operate at record electric field stress and power density, required more careful design, materials selection, fabrication, assembly, maintenance, and diagnostics to monitor performance. Fourth, a multi-terawatt, super-power generator of this size required a sizeable step function in the resources required to assemble, test, optimize, and operate in an effective manner. Finally, PBFA was an engineering construction project with a particular purpose in mind--to achieve significant thermonuclear yield from inertially confined fusion reactions. In order to conduct experiments on the time scale required by the DOE ICF Program, the accelerator and facility therefore had to be brought to a reliable, optimized operational status earlier in its lifetime than any other prior facility.

Whereas the earlier accelerators could be designed, assembled, and utilized for pulsed power development and fusion studies by one or two small research groups, the complexity of PBFA and the operational characteristics it was required to satisfy necessitated interactions between and contributions from many research

groups within Sandia's Fusion Program. These interactions were accomplished by forming a PBFA-I Project Team whose members contributed to the physics, electrical, mechanical, pulsed power, and operations engineering of the facility. In this manner, the PBFA Facility, consisting of an integrated building, utilities, accelerator, control/monitor system, data acquisition system, and other specialized supporting subsystems (insulating gas, water, oil, vacuum), was engineered.

Important Concepts in the Engineering
of Super-Power Generators

A number of important design, implementation, and operations concepts were developed during the PBFA Project, and this information will be incorporated into design of future installations. Some of these included:

During Design

1. A formalized information exchange procedure is required during the formulation of early design criteria in order to keep all project members properly informed. An Engineering Change Order (ECO) System was found to be beneficial in incorporating design changes.
2. Building and testing a prototype module to evaluate component mechanical and electrical properties before committing to a full production run is necessary.
3. A higher success rate will be achieved if the pulsed power, electrical, mechanical, and operational criteria for the Facility are developed by pulsed power, electrical, mechanical, and operations engineers, respectively.
4. Information solicited from personnel who assembled and operated previous accelerators is extremely valuable. The information collection process was accomplished by encouraging a participating environment for the Project Team, including the experienced personnel in the conceptual design criteria meetings, and then documenting and disseminating this knowledge to other Project Team members.

During Assembly/Test

1. Fabricated hardware delivery invariably causes problems; a flexible assembly schedule with contingency plans is desirable. Locating multiple vendors for critical component fabrication will aid this problem.
2. A super-power generator progresses through stages of heavy-, medium-, and light-duty construction of the support facility in addition to the actual assembly of the accelerator components. It is desirable

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- to have qualified individuals to act as single-point contacts to coordinate and expedite the interface problems during these activities.
3. "Conventional" support systems, e.g., oil, water, electrical power, insulating gas, can no longer be considered conventional when they approach the size required to support a super-power generator. It is desirable to install these systems with sufficient time to test and correct deficiencies. Documentation verifying the acceptance tests of these systems is necessary.
 4. It is desirable to document compromises and design changes made out of expediency (i.e., due to scheduling and assembly problems), so that these changes can be upgraded, modified, or retrofitted with reliable configurations during later operational phases.

During Early Operations

1. It is time and cost effective to perform good engineering design "up front", i.e., early in the project, rather than by retrofitting later during operations.
2. Human engineering aspects must be included into designs which require maintenance and personnel interfaces.
3. Conservative electrical and mechanical designs should be employed if long-term operational reliability and efficient operations are to result.
4. Numerous operations difficulties encountered in bringing PBFA-I to operational status appear to be generic to large multi-module, state-of-the-art pulsed power facilities, no matter how specialized each may be. It is probable that a workshop on these difficulties organized by operations-oriented groups could uncover some of these "universal truths".

During Later Operations

As PBFA-I continues to reach the operational status necessary to field fusion physics experiments, improvements must be made in the operating efficiency of the facility, i.e., increasing the number of useful accelerator shots and the amount of information learned per shot while decreasing the price (time and dollars). This concern is, of course, common to virtually all large-scale research facilities. A potential solution may lie in the recognition and development of a new field of technology referred to in this paper as "operations engineering". Pulsed power operations engineering can be described as the field of activities directed toward maximizing the learning rate on a state-of-the-art pulsed power facility while minimizing the time and cost of the knowledge gained. Some of the concepts comprising this technology are:

1. Automation techniques -- the development and optimization of computer controlled control/monitor and data acquisition systems to maximize the speed and accuracy of performing large numbers of routine procedures and sequences;
2. Human engineering/interface of personnel to equipment -- effective hardware and facility mechanical design which eases maintenance requirements, reduces errors, and assists personnel in performing taxing or tedious jobs;
3. Planning/coordinating/resource utilization skills -- management capacity for organizing multiple or simultaneous activities, e.g., conducting experiments, performing both fault mode and preventative maintenance, improving and upgrading accelerator and support systems, and effectively utilizing talents of multi-man operating crews;
4. Information input/output methodology -- collecting, documenting, and disseminating a variety of information to varied audiences (e.g., multi-module accelerator amplitude and synchronization data, experimental diagnostics data, accelerator timing and cabling logic diagrams for users, reliability and lifetime statistics for component designers) using presentation media which are easily and quickly understood;
5. Observation processing/experimentation techniques -- recording and analyzing anomalies, unusual component operation, synergistic effects and unanticipated experimental results, establishing cause and effect relationships, disseminating information to appropriate staff on the success or failure of design compromises, devising and evaluating upgrades and retrofits for improved performance;
6. Advanced technology transfer -- training and education of staff and technicians in pulsed power concepts and operating theory of new accelerators;
7. Troubleshooting/preventative maintenance schemes -- development of fault tree diagnostics procedures, operating modes and hardware for fast, easy accelerator and subsystem checkout, establishment of spare subassembly, piecpart, and operating supply inventory, setup of assembly line refurbishment procedures to reduce routine maintenance downtime;
8. Experimenter/facility interfacing -- coordination, staging, and assistance in the setup and execution of user group physics experiments, provision of necessary experimental hardware (e.g., cables, connectors, attenuators, trigger generators, tools, mechanical fixtures), assembly and work space, machine shop capability, and skilled manpower support necessary to efficiently field a complex experiment.

The Sandia Particle Beam Fusion Program will continue to advance this technology to effectively utilize

the pulsed power capability of PBFA-I and future super-power generators.

Phases in the Development of Super-Power Generators

In looking back at the evolution of PBFA from its design through its first shot and into its operational phase, the PBFA-I Project performance was analyzed to develop a more effective plan for the design, implementation, and operation of future generators with multi-terawatt class complexity.

The sequence of events in this plan is shown in Figure 1. The combination of technical collaboration, phased design, performance evaluation of a full-scale prototype, documented assembly and test, and development into a mature facility utilizing operations engineering will result in time and cost effective production of super-power generators.

Present Operational Status of PBFA

Final Configuration of Accelerator and Subsystems

An electrical schematic² of the components for a single module in the accelerator oil section (energy storage), water section (pulse forming), and vacuum section (power flow), along with the charging and two main triggering systems, is shown in Figure 2. Presently, the accelerator is configured to deliver 18 positive and 18 negative polarity outputs by utilizing a unique voltage inverting network³ in the pulse forming section to invert the electric field vector for alternating modules. This arrangement can then provide either + 2 MV, - 2 MV, or 4 MV accelerating potentials and allows experimental flexibility.

Data from various electrical diagnostic monitors show a typical spread of 15 nsec or less in the synchronization of the electrical outputs of both the 18 positive modules and of all 36 modules, in various experiments (see Figure 3), and an output power and energy which achieved the design criteria of 30 TW and 1 MJ, respectively.⁴

Accelerator Activity

The first full-power, 36-module shot was achieved on June 28, 1980; on July 1, responsibility for running

the Facility was transferred to the Operations Division. From that time, the Facility has achieved operational status by completing the following activities (as summarized in the PBFA shot record, Figure 4): interfacing of the control/monitor and data acquisition systems, calibration of electrical diagnostic monitors, establishment of a stable operating point, characterization and optimization of the power flow chain, performance of advanced magnetically insulated power flow studies which successfully convoluted power from 18 or 36 separate modules into a single radial triple-disc feed, and conduction of preliminary ion beam generation experiments.

Conclusion

The knowledge and experience gained during the design and implementation of PBFA-I has allowed Sandia's Fusion Program to bring the accelerator to a reliable, operational status in less than one year, i.e., quicker than prior generators, even with a significant increase in the complexity of the Facility. Techniques established during the PBFA-I Project should greatly aid in the development of future super-power generators, especially the next generation Particle Beam Fusion Accelerator, PBFA-II.

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FIGURE 1. PHASES IN THE DEVELOPMENT OF A SUPER-POWER GENERATOR

- I. FORMATION OF A PLANNING TEAM
 - A. Administration/Coordination Personnel
 - B. Drafting/Design
 - C. Mechanical Engineering
 - D. Electrical Engineering
 - E. Pulsed Power Technology
 - F. Control/Monitor Technology
 - G. Data Acquisition Technology
 - H. Facilities Design Technology
 - I. Operations Technology
 - J. Safety
 - K. User/Experimenter Technology
- II. ACCELERATOR CONCEPTUAL DESIGN CRITERIA
 - A. Electrical, Mechanical, and Operational Requirements and Constraints
 - B. Necessary Component and Subsystem Interfaces
 - C. Fault Mode Analysis and Development of Safe Failure Modes
 - D. Support System and Housing Facility Criteria
 - E. Control/Monitor Criteria
 - F. Electrical Diagnostic Requirements
 - G. Operations and Maintenance Criteria
 - H. Reliability/Lifetime Considerations
 - I. Operating Environment for Support Subsystems
 - J. EMP Shielding
- K. Ionizing Radiation Shielding
- L. Quality Specifications
- III. PRELIMINARY DESIGN PHASE
- IV. FINAL DESIGN PHASE
- V. PROCUREMENT AND FABRICATION OF PARTS
- VI. ENGINEERING AND PULSED POWER EVALUATION OF FIRST PROTOTYPE MODULE
- VII. PROCUREMENT AND ACCEPTANCE OF PRODUCTION COMPONENTS, STAGING, INVENTORY, AND SPARES
- VIII. COMPONENT, SUBSYSTEM, AND FULL ACCELERATOR ASSEMBLY
- IX. PULSED POWER TESTING
 - A. Support Subsystems (charging and firing)
 - B. Combined Systems to Evaluate Synergistic Effects
- X. POWER FLOW CHARACTERIZATION AND OPTIMIZATION
- XI. DEVELOPMENT INTO AN OPERATIONAL FACILITY
 - A. Establish Stable Operating Points
 - B. Hardware Modifications, Upgrades, Retrofits from Operating Experience
 - C. Final Interfacing of Support Systems
 - D. Development of Operating Procedures and Technician Training
- XII. DOCUMENTATION OF FINAL SYSTEM CONFIGURATIONS, FEEDBACK INFORMATION LOOPS BETWEEN OPERATIONS, ENGINEERING, AND PULSED POWER TECHNOLOGY
- XIII. FINAL DOCUMENTATION FOR PLANNING/PROJECT TEAM
- XIV. MATURE OPERATIONAL DEVELOPMENT

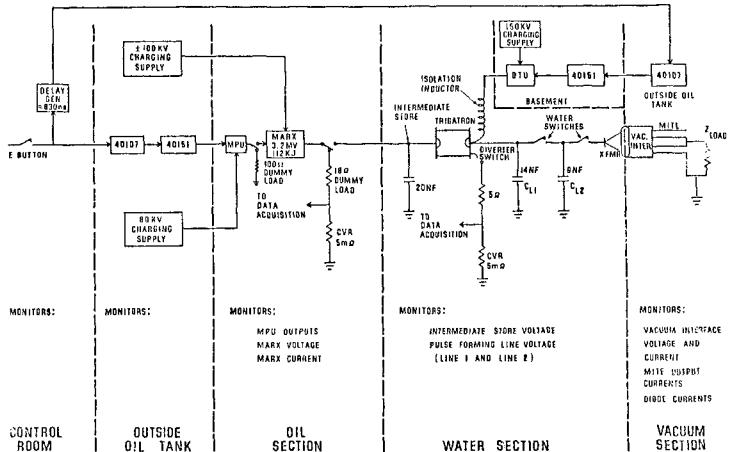
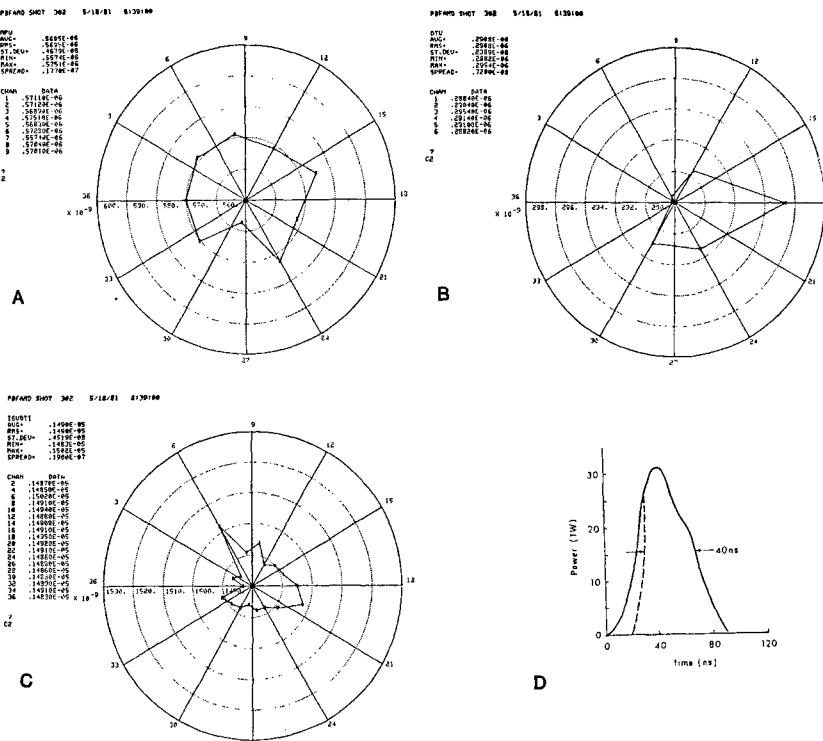


FIGURE 2. ELECTRICAL SCHEMATIC OF THE PBFA-I CHARGING AND FIRING SYSTEMS AND POSITIONS OF ELECTRICAL DIAGNOSTIC MONITORS

FIGURE 3. ACCELERATOR ELECTRICAL OUTPUT DIAGNOSTICS

- (a) Symmetry of trigger pulses from the 9 Marx pulser units (spread = 18 ns)
- (b) Symmetry of trigger pulses from the 6 output trigger units firing the trigatron switches (spread = 7 ns)
- (c) Symmetry of voltage pulse in the water section for an 18-module experiment (spread = 19 ns)
- (d) Output power pulse shape from a 36-module experiment.



MONTH/YEAR	NO. SHOTS	EXPERIMENT
MAY 1981	5	18 MODULES FEEDING A SINGLE MAGNETICALLY INSULATED DIODE; PROTON BEAM GENERATION AND FOCUSING STUDY
APRIL	20	PERFORMANCE MONITORING AND EVALUATION SYSTEM CALIBRATION; TRIGATRON SYNCHRONIZATION
MARCH	17	- 4 MODULE, 4 MV CONVOLUTE DEVELOPMENT - 4 MODULE, 4 MV TRIPLE-DISK FEED OPTIMIZATION
FEBRUARY	6	- 34 MODULE MARX SYNCHRONIZATION - 2 MODULE CONVOLUTE DIAGNOSTIC DEVELOPMENT
JANUARY	7	MITL ALIGNMENT TECHNIQUES FOR TRIPLET FEED EXPERIMENT; HIGH CURRENT CONTACT DEVELOPMENT FOR CONVOLUTE HARDWARE
DECEMBER 1980	11	VACUUM INTERFACE ALIGNMENT TECHNIQUES; TRIPLE-DISK FEED SHORT SHOTS FOR MONITOR DEVELOPMENT
NOVEMBER	3	INJECTOR ALIGNMENT DEVELOPMENT; TRIGGER SYNCHRONIZATION OPTIMIZATION; FINAL POWER FLOW CHARACTERIZATION SERIES WITH 36 DIODES (1 MJ, 30 TW OPERATING POINT)
OCTOBER	50	36 MODULE MARX SYNCHRONIZATION AND SUBSYSTEM OPTIMIZATION; INITIAL POWER FLOW CHARACTERIZATION SHOTS
SEPTEMBER	25	CONTROL/MONITOR SYSTEM INTERFACING; TRIGGER SYSTEM TROUBLESHOOTING; SETUP FOR 36-MODULE DIODE SHOTS
AUGUST	24	2 MODULE POWER FLOW CHARACTERIZATION, MARX AND TRIGATRON SIMULTANEITY TESTS
JULY	24	2 MODULE DIAGNOSTIC CALIBRATION AND MARX TEST SHOTS; MINOR REPAIRS TO SUBSYSTEMS AFTER FIRST SHOT
JUNE 28, 1980	1	FIRST FULL-POWER, 36-MODULE SHOT INTO DIODES

FIGURE 4. PBFA-I SHOT SUMMARY SINCE FIRST FIRING